Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **High-Speed Widely-Tunable >90% Quantum-Efficiency Resonant Cavity Enhanced p-i-n Photodiodes**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Boston University,Department of Electrical and Computer Engineering,Boston,MA,02215**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of IEEE Lasers and Electro-Optics Society 1998 Annual Meeting, Vol. 1, 1-4 December 1998, pp. 157-158.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**2**	

8:45am - 9:00am
WB2

High-Speed Widely-Tunable >90% Quantum-Efficiency Resonant Cavity Enhanced p-i-n Photodiodes

Necmi Biyikli[a], Ibrahim Kimukin[b], Orhan Aytur[a], Mutlu Gökkavas[c], Gokhan Ulu[c], R. Mirin[d], D. H. Christensen[d], M. Selim Ünlü[c], and Ekmel Özbay[b]

High-speed, high-efficiency photodetectors play an important role in optical communication and measurement systems. [1]. Both Schottky photodiode [2], and p-i-n photodiode [3] offer a high-speed performance to fulfill the needs of such high-speed systems. However, the efficiency of these detectors have been typically limited to less than 10%, mostly due to the thin absorption region needed for short transit times. One can increase the absorption region thickness to achieve higher efficiencies. But this also means longer transit times that will degrade the high-speed performance of the devices. Resonant cavity enhanced (RCE) photodetectors potentially offer the possibility of overcoming this limitation of the bandwidth-efficiency product of conventional photodetectors [4-5]. The RCE detectors are based on the enhancement of the optical field within a Fabry-Perot resonant cavity. The increased field allows the usage of thin absorbing layers, which minimizes the transit time of the photo-carriers without hampering the quantum efficiency. High-speed RCE photodetector research has mainly concentrated on using p-i-n type photodiodes, where near 100% quantum efficiencies along with a 3-dB bandwidth of 17 GHz have been reported [6]. Recently, we have fabricated RCE type Schottky photodiodes with 50% quantum efficiency, and a 50 GHz frequency performance[7-8]. In this paper, we report our work on design, fabrication, and testing of widely tunable high-speed RCE p-i-n photodiodes for operation around 820 nm.

The details of the epitaxial structure we have used in this work is given in the Table 1. The bottom Bragg mirrors are made of quarter-wave stacks ($Al_{0.20}Ga_{0.80}As/AlAs$) designed for high reflectivity at 820 nm center wavelength. The structure was grown by solid-source MBE on semi-insulating GaAs substrates. The carrier trapping was avoided by the graded interfaces of absorbing layer.

The samples were fabricated by a microwave-compatible fabrication process. First, ohmic contacts to the N+ layers were formed by a recess etch that was followed by a self-aligned Au-Ge-Ni liftoff. The p+ ohmic contact was achieved by an Au/Ti lift-off. The samples were then rapid thermal annealed.

Material	Doping (cm^{-3})	Thickness (nm)
GaAs	p^+ $2x10^{18}$	20
$Al_{0.2}Ga_{0.8}As$	p^+ $2x10^{18}$	200
$Al_{0.2}Ga_{0.8}As$ ®GaAs	undoped	38
GaAs	undoped	470
GaAs® $Al_{0.2}Ga_{0.8}As$	undoped	38
$Al_{0.2}Ga_{0.8}As$	n^+ $2x10^{18}$	390
$Al_{0.2}Ga_{0.8}As$	undoped	180
Bragg Mirror (24 pairs)		
Semi Insulating GaAs		

Table 1: Epitaxial structure of the sample

Using an isolation mask, we etched away all of the epilayers except the active areas. Then, we evaporated Ti/Au interconnect metal which formed coplanar waveguide (CPW) transmission lines on top of the semi-insulating substrate. The next step was the deposition and patterning of a 2000 Å thick silicon nitride layer. Finally, 1.0 micron thick Au layer was used as an airbridge to connect the center of the CPW to the top p+ ohmic metal. The resulting p-i-n diodes had breakdown voltages larger than 15 V.

Photo response measurements were carried out in 750-850 nm wavelength range, by using a tungsten-halogen projection lamp as the light source and a single pass monochromator. Output of the monochromator was coupled to a multimode fiber. The monochromatic light was delivered to the devices by a lightwave fiber probe, and the electrical characterization was carried out on a probe station. The incident power spectrum was measured by a calibrated optical powermeter. For photo spectral measurement large area photodiodes were chosen (100x100 to 250x250 mm^2) to ensure all of the optical power is incident on the active area. The top p+ layers were etched in small steps, and the tuning of the resonance wavelength within the Bragg mirror's upper and lower edges was observed.

[a] Department of Electrical and Electronics Engineering, Bilkent University, Bilkent, Ankara 06533, Turkey.
[b] Department of Physics, Bilkent University, Bilkent, Ankara 06533, Turkey.
[c] Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA.
[d] Optoelectronics Division, National Institute of Standards and Technology, Boulder, CO 80303, USA.

0-7803-4947-4/98/$10.00 ©1998 IEEE

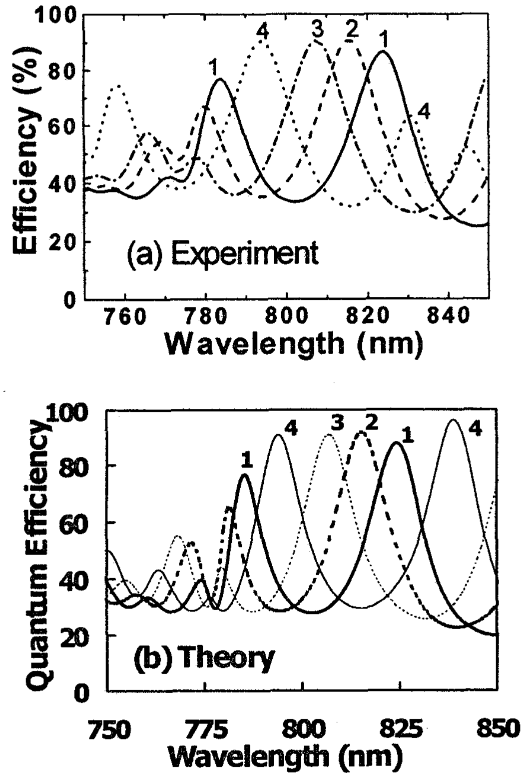

Figure 1: (a) Experimental and (b) theoretical photoresponse of the p-i-n RCE photodiode.

Figure 1(a) shows the spectral quantum efficiencies of devices with different recess etch. Device 1 corresponds to as-grown wafer, while devices 2, 3, and 4 have been recess etched 21, 44, and 79 nm respectively. Figure 1(b) shows the transfer matrix method based theoretical simulations of the same devices. The no-etch peak quantum efficiency (86%) increases to 92% after the top absorbing GaAs cap layer is removed. The peak quantum efficiency remains almost constant afterwards until the resonance wavelength reaches to the lower edge of the Bragg mirror (790 nm). At this point, the second resonance appears around the upper edge of the Bragg mirror. As seen in Fig. 1, the resonance wavelength can be tuned from 850 nm to 795 nm with peak efficiencies above 85%. The full-width at half maximum (FWHM) of the devices is around 15 nm. The data shown in Fig. 1(a) is obtained at zero bias. The measured quantum efficiencies do not change at higher reverse biases, as the undoped active region is already depleted at zero bias.

High speed measurements were made with 1 ps FWHM optical pulses obtained from a Ti-Sapphire laser operating at 820 nm.

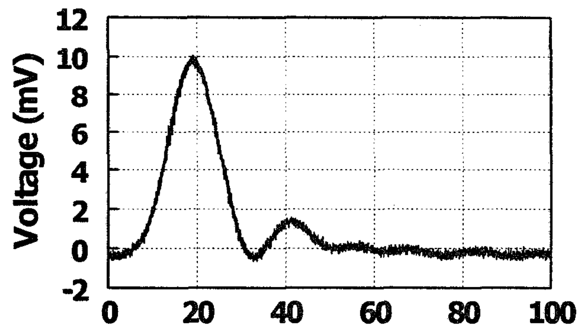

Figure 2: Pulse re[illegible]sample

Figure 2 shows the temporal response of a small area photodiode measured by a 50 GHz sampling scope. The measured photodiode output has a 12 ps FWHM. The Fourier transform of the data has a 3-dB bandwidth of 40 GHz. If the scope response is deconvolved, the device has a 3-dB bandwidth of 50 GHz. This result is in good agreement with our calculations, which predict a 3-dB bandwidth of 51 GHz.

This work was supported in part by the Turkish Scientific and Technical Council under Project 197-E044, in part by the Office of Naval Research under Grant N00014-96-10652, and in part by the National Science Foundation International Collaborative Research under Grant INT-9601770.

REFERENCES

[1] E. Bowers and Y. G. Wey in *Handbook of Optics*, chap. 17, Michael Bass (ed.), McGraw-Hill, New York, 1995.

[2] E. Özbay, K. D. Li, and D. M. Bloom, *IEEE Photon. Technol. Lett.*, vol. 3, pp. 570-572, 1991.

[3] Y. G. Wey, M. Kamegawa, A. Mar, K. J. Williams, K. Giboney, D. L. Crawford, J. E. Bowers, and M. J. Rodwell, *J. Lightwave Technol.*, vol. 13, pp. 1490-1499, 1995.

[4] M. S. Ünlü and S. Strite, "Resonant cavity enhanced (RCE) photonics devices," *J. Appl. Phys. Rev.*, vol. 78, pp. 607-639, 1995.

[5] H. Nie, K.A. Anselm, C. Lennox, P. Yuan, C. Hu, G. Kinsey, B.G. Streetman, and J.C. Campbell, *IEEE Photon. Tech. Lett.* **10**, 409 (1998).

[6] C. C. Barron, C. J. Mahon, B. J. Thibeault, G. Wang, W. Jiang, L. A. Coldren, and J. E. Bowers, *Electron. Lett.*, vol. 30, pp. 1796-1797, 1994.

[7] E. Özbay, M. S. Islam, B. M. Onat, M. Gökkavas, O. Aytür, G. Tuttle, E. Towe, R. H. Henderson, and M. S. Ünlü, *IEEE Photon. Technol. Lett.*, vol. 9, pp. 672-674, 1997.

[8] M. S. Unlu, M. Gokkavas, B. M. Onat, E. Ata, E. Ozbay, R. P. Mirin, K. J. Knopp, K. A. Bertness, D. H. Christensen, *Applied Physics Letters*, volume **72**, p. 2727 (1998).